P2.9   HURRICANE ISABEL: A NUMERICAL MODEL STUDY OF STORM SURGE
ALONG THE EAST COAST OF THE UNITED STATES

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1. Introduction

On the 6th of September 2003, a westward moving, tropical wave in the far eastern Atlantic began to organize and evolve into tropical storm Isabel. By September 7, Isabel had become a full-fledged hurricane and began to move west-northwest. Isabel continued her northwest track through the 8th and 9th, intensifying into a major hurricane. By September 11th, Isabel had become a Category 5 hurricane on the Saffir-Simpson Scale, and maintained this high level of intensity through September 15th. During this time Isabel took a more westward track, until it began to turn northwestward on the 15th. On the 16th, Isabel began to weaken and headed in a north-northwestward direction toward the North Carolina coast. On September 18th at approximately 17Z, Isabel made landfall near Drum Point, North Carolina as a Category 2 hurricane with sustained winds near 100 mph and a minimum central pressure of 957 mb. Hurricane forecast winds extended 115 miles from the center of its large eye with tropical storm force winds extending 345 miles out from the center. By 1500Z (11 am EDT) on September 19th, Isabel was downgraded to a tropical depression located northeast of Cleveland, Ohio and was moving rapidly to the north (Figure 1).
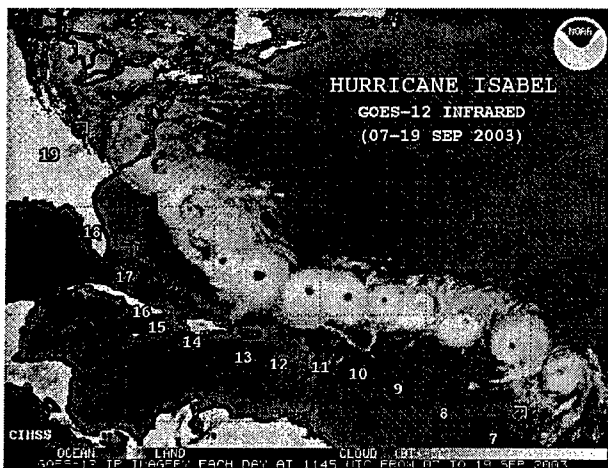

Figure 1. Track of Hurricane Isabel, courtesy of NOAA.

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Isabel brought hurricane conditions to eastern North Carolina and southern Virginia and tropical storm conditions to a larger area extending from North Carolina northward to New York. Extensive storm surge flooding occurred along the Atlantic coast and into Chesapeake Bay as well as in the Potomac and James Rivers. Rainfall amounts of 6-12 inches were recorded at locations in North Carolina and Virginia.

According to data from the U.S. Geological Survey, the total amount of water that entered Chesapeake Bay during Isabel and the subsequent 7-day period (September 19-25, 2003) was 8 times the normal amount of water for that period in September (http://chesapeake.usgs.gov/chesbay/isabelinfo.pdf).
By comparison, the largest observed amount of total water entered Chesapeake Bay during Tropical Storm Agnes (June, 1972) and was 16.5 times the norm.

Isabel was the most costly storm to hit the coastal United States in 2003. Isabel caused at least 47 deaths and an estimate of over 4 billion dollars in damages (Ross and Lott, 2003). Strong winds destroyed homes, businesses and knocked down trees and power lines. Several million homes and businesses were without power. Severe flooding due to the strong storm surge and large wave impact as well as heavy rain damaged homes, businesses, marinas and roads.

During the past several decades, our understanding of the dynamics and thermodynamics of tropical storms has grown tremendously. Along with this understanding, has come a greatly improved forecasting capability. A suite of numerical models is presently used by the National Hurricane Center to forecast the path taken by tropical storms. The general track of hurricane Isabel was predicted by the National Hurricane center at least three days before landfall yet, hurricane Isabel was responsible for both a number of deaths and property damage. One particularly hard hit area was Baltimore, Maryland located at the northwestern extreme of Chesapeake Bay. Although Baltimore only received 3 inches of rain from Isabel, the associated storm surge destroyed marinas and flooded the historic Fell's Point neighborhood.   When questioned as to the quality of warning information associated with the storm's strike, the Mayor of Baltimore stated "We had three days to prepare for this. We prepared for the worst case scenario and that's what we got" (CNN.COM, Sept 20, 2003).

Numerical ocean models can be used to both forecast and hindcast storm surge events. These models use the wind and pressure forcing associated with a

hurricane or tropical storm to determine the magnitude of the associated storm surge. In addition, these models can include the effect of tides on the water level. In this paper, we will use numerical model forecasts and hindcasts, compared to the observed water level data, to discuss the dynamics of the surge associated with hurricane Isabel, to determine the fidelity of the model forecasts and to try to determine what caused this "worse case scenario" to come about.

2. The Numerical Models

The Naval Research Laboratory has built a globally relocatably tide-surge forecast system called "PCTides". The PCTides system (Figure 2) is composed of a 2-D barotropic ocean model driven by tidal forcing and/or wind and surface forcing (Preller et al., 2002, Blain et al., 2002).
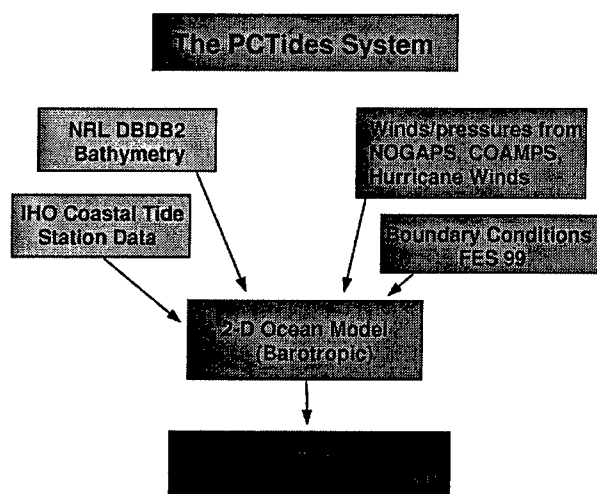

Figure 2. Components of the PCTides system.

PCTides is applied to the user's area of interest to provide a hindcast or forecast of tidal amplitude and phase as well as 2-dimensional barotropic ocean currents. The PCTides system uses the solutions from a global tide model (FES99, Lefevre et al., 2000) to provide global boundary conditions. The system also contains a 2-minute global bathymetry data base, the NRL-DBDB2 database, to define the model's geometry and bathymetry (http://www7320.nrlssc.navy.mil/DBDB2_WWW/).
PCTides may be run in a mode loosely constraining the solutions to a subset of more than 4000 tidal observation stations from the Canadian Hydrographic Office's International Hydrographic Observations (IHO) data base (Anonymous, 1988).

Wind forcing for PCTides comes from a number of sources. If the user has access, he may use the Navy's real time forecast winds from the Navy Operational Global Atmospheric Prediction System (NOGAPS)

(Hogan and Rosmond, 1991) or the Coupled Oceanic and Atmospheric Mesoscale Prediction System (COAMPS) (Hodur, 1997). The PCTides system also includes a "hurricane model" developed by Holland (1980). Based on this model, a hurricane may be built that can provide surface pressures and winds to drive the 2-dimensional barotropic ocean model and generate storm surge. The Holland model has been tested extensively and has been found to provide a good representation of wind fields in the vicinity of a tropical cyclone.

3. Hurricane Isabel numerical model experiments

Both before and after the landfall of Hurricane Isabel, the PCTides system was set up and run to simulate the effects of the storm on water levels in the coastal areas along its path. Eight experiments in total were carried out. Each of these experiments used the same model domain (set up to cover the region of most probably impact), grid resolution (3 km) and tidal forcing. No data assimilation of coastal station data was included in any of the experiments. Each experiment produced output from a set of eight pre-selected tidal stations, each co-located with a NOAA water level observing station. Tidal heights and 2-D barotropic ocean currents were written out at each station at a frequency of 12 minutes.

The eight experiments differed in the type of wind forcing that was used. The first experiment, considered the standard or baseline, used no wind. The next four experiments were run in a forecast mode before Isabel made landfall. NOGAPS and COAMPS 48-hour forecast winds and surface pressures, from 00Z on September 18 to 00Z on September 20[th,] were used in two of these cases.

The Holland tropical cyclone model was used to generate a hurricane forecast for the other two cases. Required input for the Holland model when used for a forecast is: the observed starting location of the storm (31.1N, 73.3W) and the time of the observation (2100Z on September 17, 2003). The storm must also be given an average central pressure (955 mb), an average forward speed (25 km/hr) and a final location for the storm which could be the land fall location or a location further inland (41.5N, 79W). The starting time and location as well as the final location was obtained from the National Hurricane Center's (NHC) forecast/advisories. The PCTides forecasts were generated in real time shortly after the NHC's 2100Z advisory/forecast for September 17th was available and prior to Isabel's landfall. The starting location was taken from the observed storm location at 2100Z and the final location was taken from the forecast position for 1800Z on September 19th provided by the NHC advisory from 2100Z September 17th (NHC advisory/forecast 47).

During the simulation, the storm moves in a straight line between the starting and ending locations at a constant speed. The ambient environmental pressure and the parameter b, discussed below, are set to the constants

1005 mb and 1.75 respectively for all runs discussed here. A final and important input parameter is the radius of maximum winds (RMW). For this study, the difference between the two forecast cases is the size and strength of the storm. In the first case, the RMW was set to 60 km while in the second case, the storm is made larger by setting the RMW to 90 km.

The Holland model uses these parameters to define a tropical cyclone in the following way. The pressure P (hPa) at radius r is derived as follows:

$$P = P_c + (P_n - P_c)e^{-(r_m/r)^b}$$

where P_c is the central pressure, P_n is the environmental pressure (the climatological mean for the region and month), r_m is the radius of maximum winds and b provides a scaling on the profile shape. The parameter b is empirically defined by

$$b = 1.5 + (980 - P_c)/120$$

The symmetric, gradient-level azimuthal wind component is estimated by

$$v = \left[b\left(\frac{r_m}{r}\right)^b \frac{(P_n - P_c)}{\rho} e^{-(r_m/r)^b} - \frac{r^2 f^2}{4} \right]^{\frac{1}{2}} - \frac{rf}{2}$$

where ρ is the air density and f is the Coriolis parameter.

A first order asymmetry is included in the storm by adding the hurricane's translation to the symmetric field and rotating the field so that the maximum wind is 70° to the right of the direction of hurricane's motion. The radial wind field is constructed by rotating the flow to a constant inflow angle of 25° outside the radius of maximum winds.

It is important to note that the tropical cyclone model is not expected to represent the full field of synoptic scale features with a high degree of accuracy. The critical aspect for storm surge and wave forcing is that the model parameterizes the mesoscale forcing in the vicinity of the maximum winds reasonably well.

The final three cases were hindcast experiments using the Holland model to build the storm. In these cases the observed locations from Isabel's track at six-hourly intervals, the associated observed minimum pressure values and an estimate of the radius of maximum winds for each observation were used as input. The three cases varied in the value chosen for the RMW using 70 km, 90 km and 100 km respectively. The NHC observations indicated that 100 km was a good estimate of the RMW for Isabel. Figure 3 shows the model domain, station locations, the observed track of hurricane Isabel and the forecast tracks from the NOGAPS, COAMPS and Holland models.
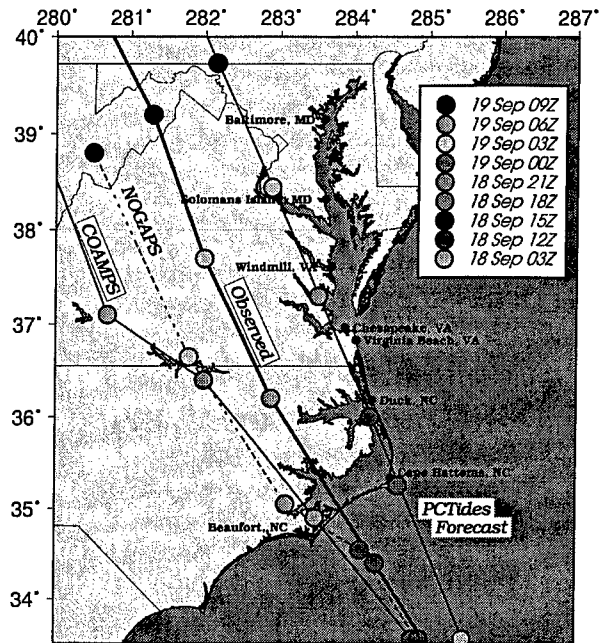

Figure 3. Model domain with station locations, Isabel's observed track forecast by the NOGAPS, COAMPS and PCTides Forecast using the Holland tropical cyclone model.

The experiments ran for different periods of time from 00Z on September 17, 2003 to 00Z on September 20, 2003. At a minimum, each experiment covered the time just prior to landfall through 1200Z on September 19, 2003. The details defining each experiment are listed in Table 1.

Experiment	Model	Wind Forcing	Simulation Time
1	Forecast	None	00Z 17th – 00Z 20th
2	Forecast	Holland – 60 km	21Z 17th – 22Z 19th
3	Forecast	Holland – 90 km	21Z 17th – 01Z 20th
4	Forecast	NOGAPS	00Z 18th – 00Z 20th
5	Forecast	COAMPS	00Z 18th – 00Z 20th
6	Hindcast	Holland – 70 km	21Z 17th – 15Z 19th
7	Hindcast	Holland – 90 km	21Z 17th – 15Z 19th
8	Hindcast	Holland – 100 km	21Z 17th – 15Z 19th

Table 1. Listing of Model Experiments.

4. Results

The modeled tidal height time series was compared to the NOAA observed water levels above mean lower low water (MLLW) for each of the stations shown in Figure 3. As the modeled tidal heights represent an anomaly

from a mean water level, a mean was calculated for each station from observed water levels and added to the model forecast before comparison.

The discussion of the results will be broken up into three geographic categories. The North Carolina Coast, including stations at Beaufort, Cape Hatteras and Duck; the southern Virginia coast, including Virginia Beach and Chesapeake Bay Bridge-Tunnel and the interior of Chesapeake Bay including Windmill, Solomans Island and Baltimore.

4.1 The North Carolina Coast

Isabel made landfall along the North Carolina coast between Beaufort and Cape Hatteras at approximately 1900Z on September 18th. Based on this path, Cape Hatteras, on the eastern side of the storm, would have experienced northeast to easterly winds shifting to southerly and then southwesterly winds while Beaufort, on the western side of the storm, would have experienced northeast to easterly winds shifting to northerly and then northwesterly winds. Therefore a stronger storm surge should be generated at Cape Hatteras than at Beaufort with both experiencing highest water around the time of landfall. The Duck station, also on the eastern side of the storm, would experience a surge similar to that at Cape Hatteras.

Figures 4-6 show the modeled tidal height time series compared to the NOAA observed water levels for the 3 stations along the North Carolina coast. Each figure contains four plots and each plot shows a different series of modeled tidal heights versus the NOAA observed water level. In order from bottom to the top; the bottom plot contains a time series from the model experiment with no wind forcing and the time series derived from the IHO tidal constituents at the station. This plot is used as a baseline for comparison with the other wind driven results and to verify the general modeling capabilities of PCTides to observations. The next plot contains the time series from the model run driven by NOGAPS and COAMPS forecasts. The third plot contains results from two forecast runs using the Holland model and the fourth plot contains the three hindcast results using the Holland model.

The NOAA observed water levels indicate that a peak in water level occurred at Beaufort at approximately 1840Z on the 18th. As the storm approached, the water levels increased at all three North Carolina stations. Although the data stream ended at approximately 1430 on the 18th at the Cape Hatteras and at approximately 1600Z at Duck, the high water level at the Cape Hatteras and the Duck stations probably occurred at a later time based on the timing of the peak winds (see later discussion). The water levels at Cape Hatteras and Duck were already 0.5 m higher than the maximum water level at Beaufort when the instrument stopped transmitting. This supports the concept that these locations on the

east side of the storm experienced winds that generated a stronger storm surge then occurred at Beaufort. In addition, the surge at Beaufort (the only one of the three stations still reporting after the storm passed) rapidly receded until the water levels were back to normal around 0300Z on the 19th, approximately 8 hours after landfall. It is also of interest to note that at all three stations, the local maximum tidal amplitude (Figures 4-6 d) coincides with peak storm surge and has a value ranging from 38-40 cm about the mean water level.
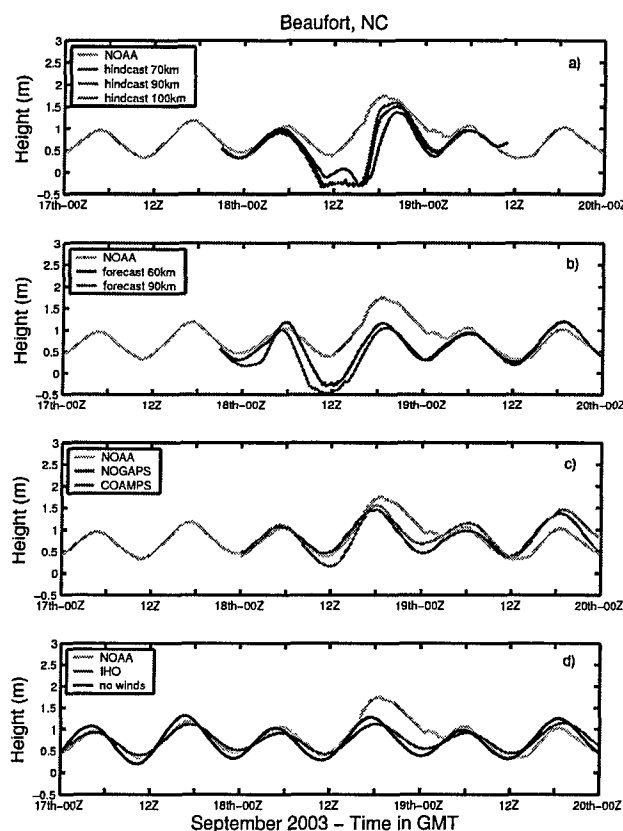

Figure 4. Observed water level above MLLW at the Beaufort, NC station versus a) Holland model hindcast using 70 km RMW, 90 km RMW and 100 km RMW, b) Holland model forecasts using 60 km RMW and 90 km RMW, c) NOGAPS and COAMPS forecast driven tidal heights and d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z on September 20th.

At all three stations, the model results capture the timing of the peak of the storm surge except in the forecast experiments where the peak occurs too early. This is due to the variability of the forward motion of the storm. Isabel was observed to move slowly as it approached the coast and then picked up speed rapidly after landfall. The storm was observed to be moving at 12 knots at 2100Z on the 17th and increased to approximately 20 knots at 0300Z on the 19th. The Holland model was set up to use a constant estimate of the forward motion of the storm in the forecast mode. The speed we chose prior to landfall (25 km/hr or 13.5

knots) assumed some increase in forward motion but not as much as was eventually observed. Using this constant average speed caused the storm to move too fast initially and then too slowly after landfall. As a result, the storm surge peaked too soon for those stations it reached first on its path and too late for those stations affected later by the storm.
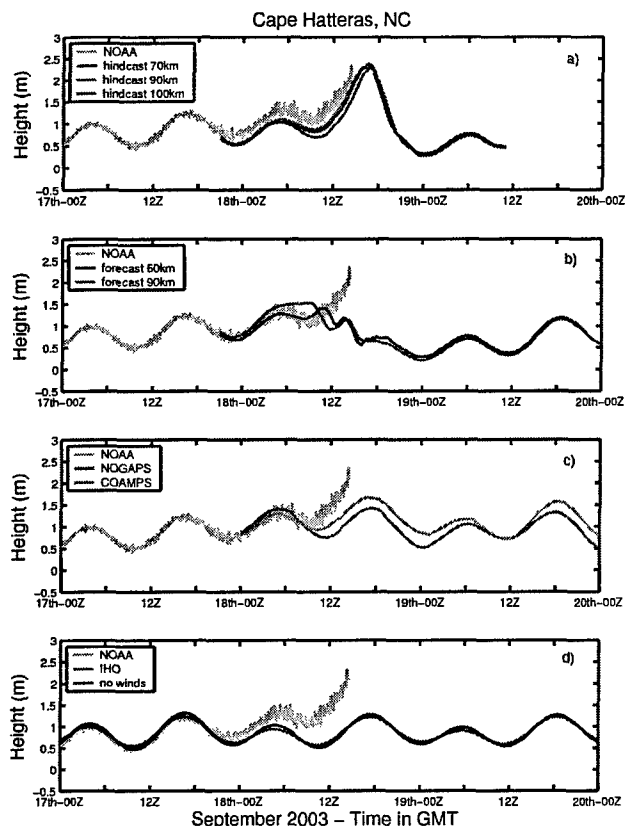

Figure 5. Observed water level above MLLW at the Cape Hatteras, NC station versus a) Holland model hindcast using 70 km RMW, 90 km RMW and 100 km RMW, b) Holland model forecasts using 60 km RMW and 90 km RMW, c) NOGAPS and COAMPS forecast driven tidal heights and d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z on September 20th.

The best overall modeled storm surge at the Beaufort Station was obtained using the COAMPS forecast winds and pressures and the Holland model hindcast using 100 km RMW. At the Cape Hatteras and the Duck stations, the hurricane model hindcasts using the 90-100 km RMW and the 100 km RMW respectively, were the most accurate when compared to the available data. The modeled hurricane forecasts generate a surge that peaks too soon at both of these stations, however, the forecast for the Duck station is generally better than that at the Hatteras station. The case using COAMPS winds produced a reasonable timing of the peak surge at these two stations, but weaker then observed.
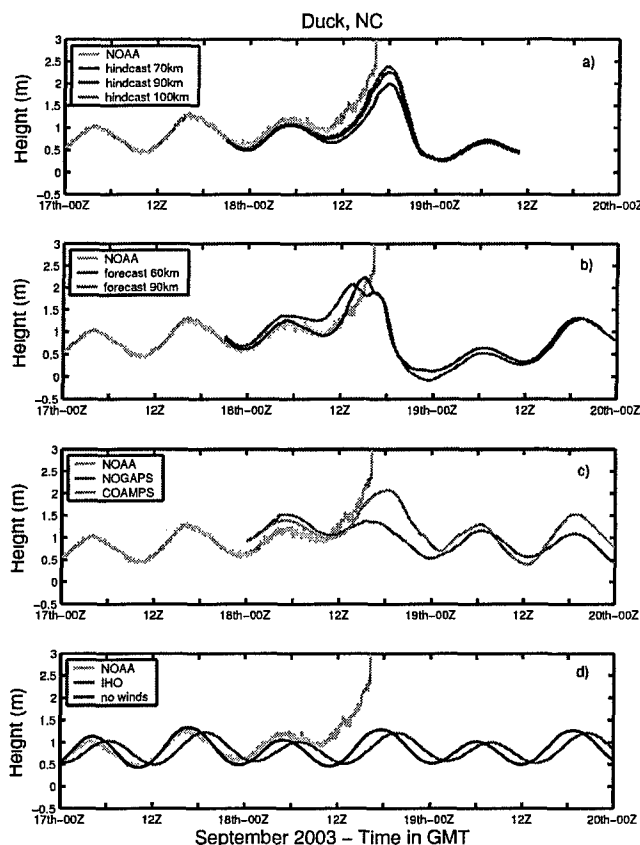

Figure 6. Observed water level above MLLW at the Duck, NC station versus a) Holland model hindcast using 70 km RMW, 90 km RMW and 100 km RMW, b) Holland model forecasts using 60 km RMW and 90 km RMW, c) NOGAPS and COAMPS forecast driven tidal heights and d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z on September 20th.

The observed winds were then compared to the modeled winds. The Duck station alone will be used as there were no wind observations at Beaufort and the Cape Hatteras after 1430Z on the 18th. Figure 7 represents the wind speed and direction at the Duck station. With respect to speed and direction, the COAMPS winds provided the best estimate while the NOGAPS winds were too weak and peaked too soon.

Interestingly, at the time of the last recorded wind speed at Cape Hatteras (not shown), the COAMPS winds were too weak and the modeled hurricane winds were in better agreement with the observations. This corresponds to the better agreement in water level between observations and the model driven with the hurricane hindcast forcing at Cape Hatteras. If the peak of the wind speed at the Duck station is used as an indicator of the peak in storm surge then the peak surge would have occurred somewhere between 1800Z-1900Z on the 18th.

The hurricane model winds at the Duck station were too strong and, in the case of the forecast hurricane, peaked too soon. The forecast winds exhibit a short, but dramatic decrease in the wind speed (approximately 1600Z on the 18th) and then an equally strong increase in wind speed accompanied by a change in wind direction. This pattern represents the movement of the eye of the storm over this station. The path of the eye passing over this station is responsible for the rapid decrease in the water level following the peak surge or maximum water level. Water is pushed toward the station as the eye approached and then rapidly pushed away as the eye passes over the station.
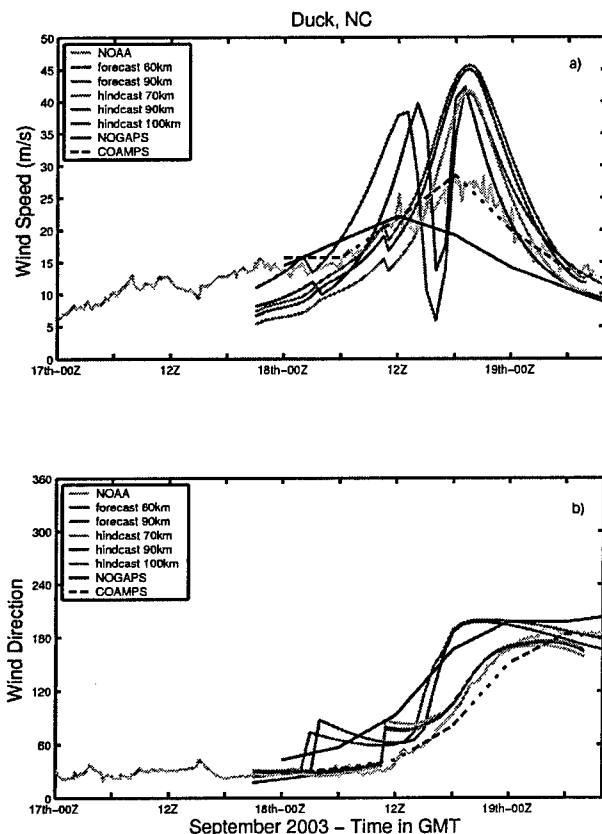

Figure 7. Observed wind a) speed and b) direction versus modeled wind speed and direction from the 7 models used in this study at the Duck, NC station.

As mentioned earlier, the hurricane model is not expected to represent the full field of synoptic scale features with a high degree of accuracy. As such the hurricane model wind and pressure fields are embedded in a background field of weak northerly winds. Figure 7 shows a strong shift in the wind direction at approximately 0300Z on the 18th in the forecast cases and at about 1000Z in the hindcast cases. This shift occurs as the hurricane approaches and the background field is modified.

4.2 The Southern Virginia Coast

As Isabel moved northwestward along her track, the coast of Virginia began to feel the strength of the storm. The southern coast of Virginia experienced the most intense part of Isabel around 1500Z-2100Z on September 18th. Figures 8-9 show the modeled water levels at the Virginia Beach and Chesapeake Bay Bridge-Tunnel stations compared to the observed water levels at the Chesapeake Bay Bridge-Tunnel observations. Although these two stations are geographically close together, the Virginia Beach station is located on the open coast while the Chesapeake station is at the mouth of Chesapeake Bay. The peak of the storm surge occurs at 1820Z on September 18th.
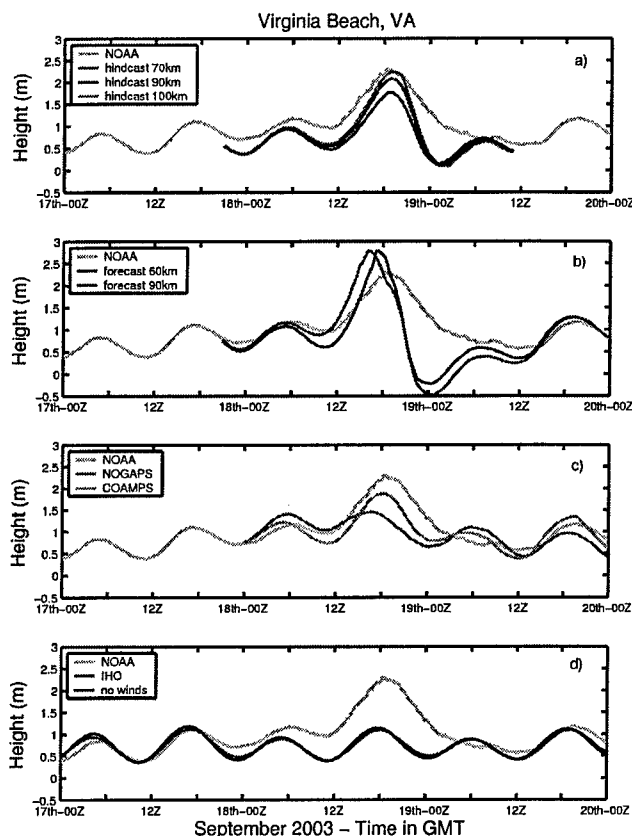

Figure 8. Observed water level above MLLW at the Virginia Beach, VA station versus a) Holland Model hindcast using 70 km RMW, 90 km RMW and 100 km RWM, b) Holland model forecasts using 60 km RWM and 90 km RMW, c) NOGAPS and COAMPS forecast driven tidal height and d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z September 20th.

The majority of the model simulations at both stations predict the timing of the peak surge reasonably well. Similar to the stations along the North Carolina coast, high tide (Figures 8-9 d) coincides with the peak of the storm surge and ranges from 34-37 cm above the mean water level. At Virginia Beach the peak of the storm

surge is best predicted by the hurricane model hindcast using the 90-100 km RMW. The forecast storm over predicts the magnitude of the storm surge while the NOGAPS model under predicts the surge. The COAMPS solution provided a better prediction of the timing and height of the peak water level. At the Chesapeake station, the forecast hurricane model (60 km RMW) provides the best peak in storm surge with both the hurricane hindcast and COAMPS/NOGAPS cases predicting a much weaker surge then observed.

wind peaks closer to the observed time but again, is larger then the observed wind. Similar to the winds at the Duck station, the forecast winds indicate the passage of the eye of the storm over the Chesapeake station. At approximately 2000Z there is a rapid reduction in wind speed followed by a rapid increased in wind speed and a shift in wind direction from east-northeasterly to southeast or southerly. The water level predicted by the forecast winds (Figure 9a) drops off drastically as the eye passes and the wind field changes direction.
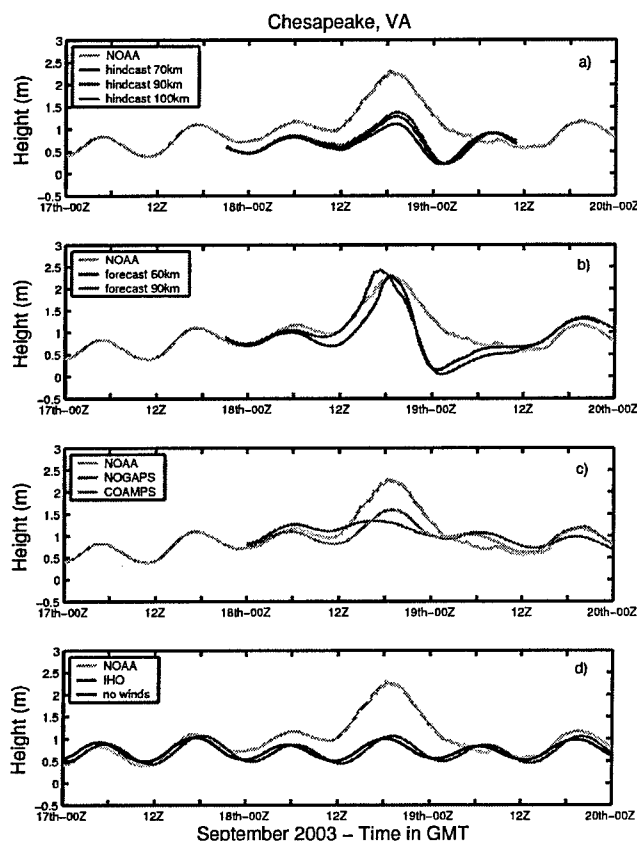

Figure 9. Observed water level above MLLW at the Chesapeake, VA station versus a) Holland Model hindcast using 70 km RMW , 90 km RMW and 100 km RWM, b) Holland model forecasts using 60 km RWM and 90 km RMW, c) NOGAPS and COAMPS forecast driven tidal height and d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z September 20th.

Figure 10 shows the wind speed and direction at the Chesapeake station. Again, the COAMPS modeled wind direction is in very good agreement with the observation however the COAMPS forecast wind speed is too weak. This explains the good agreement in the timing of peak surge and also the weakness of the surge. In the case of the hindcast hurricane, the direction of the wind compared well to observation but the wind speed is too large and peaks a few hours after the observed maximum. In the case of the forecast hurricane, the
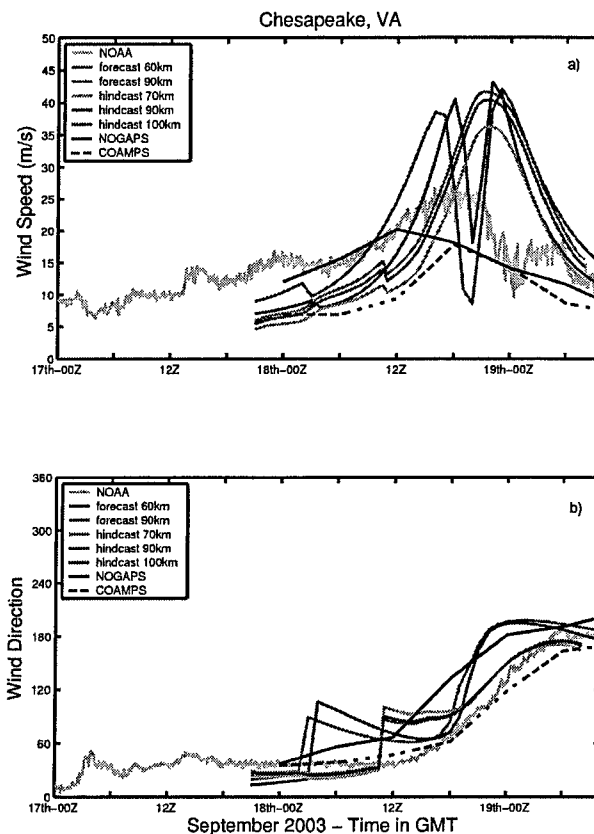

Figure 10. Observed wind a) speed and b) direction versus modeled wind speed and direction from the 7 models used in this study at the Chesapeake, VA station.

4.3 Chesapeake Bay

The mid to northern part of Chesapeake Bay experienced the most intense effects of Isabel from about 00Z to 1200Z on September 19th. At 0300Z on the 19th, Isabel was down graded to a tropical storm moving at a speed of 20 knots to the northwest and its central pressure had risen to 972 mb (up from 957 mb at landfall on the 18th). Figures 11-13 show the water level predictions versus the NOAA observed water levels for the stations at Windmill, Va; Solomons Island, Md; and Baltimore, Md.

the Chesapeake station and total distance between the Chesapeake and Baltimore stations. The distance between those two stations is approximately 265 km while the distance from the Windmill station to the Chesapeake is approximately 81 km while the distance from the Solomons Island station to the Chesapeake is approximately 159 km. Based on these distances and the observed time of peak surge at the Chesapeake and Baltimore stations, the maximum surge at the Windmill station occurred at approximately 2344Z on the 18th and at 0456Z on the 19th at Solomons Island.
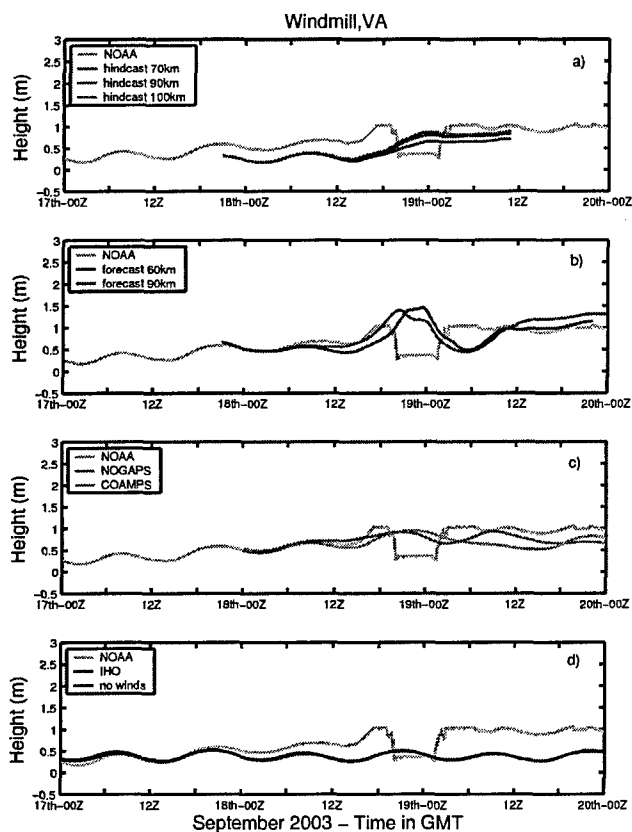

Figure 11. Observed water level above MLLW at the Windmill, VA station versus a) Holland Model hindcast using 70 km RMW, 90 km RMW and 100 km RWM, b) Holland model forecasts using 60 km RWM and 90 km RMW, c) NOGAPS and COAMPS forecast driven tidal height and d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z September 20th.
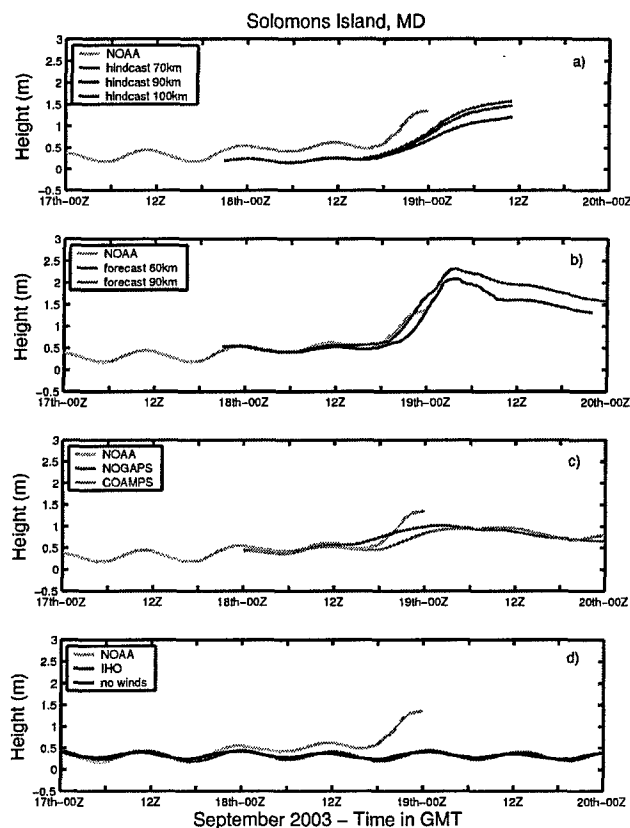
Figure 12. Observed water level above MLLW at the Solomons Island, MD station versus a) Holland Model hindcast using 70 km RMW, 90 km RMW and 100 km RWM, b) Holland model forecasts using 60 km RWM and 90 km RMW, c) NOGAPS and COAMPS forecast driven tidal height and d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z September 20th.

Water level records show that the maximum surge occurred at approximately 1200Z on the 19th at Baltimore. The observed water level records at the Windmill and Solomons Island stations are missing data at the time of peak surge and require an estimate of the time of peak surge. We assume that the storm was traveling at a constant speed from the time of peak surge at Chesapeake (1820Z on the 18th) until it reached Baltimore (1200Z on the 19th). The time of maximum surge at the Windmill and Solomons Island stations may be inferred based on their distance from

The tidal interaction with the storm surge most likely plays a minimal role at these stations. Tidal amplitudes at each of these three stations are much smaller then those at the previous stations. The maximum tidal amplitudes range from 15 cm, to 12 cm, to approximately 2cm above the mean water level at the Windmill, Solomons Island and Baltimore stations respectively. Since the true water levels and exact time of peak surge are unknown at all but the Baltimore station, where the tides are the weakest, it is hard to

draw any detailed conclusions of the impact of tides on the maximum water level.

Although the data dropout period at the Windmill station corresponds to the peak in storm surge, we can deduce from the available data that the COAMPS, NOGAPS and all of the hindcast cases underestimate the height of the peak surge while the forecast cases might overestimate the peak height. Based on the estimates of the time of peak storm surge discussed previously, the COAMPS produces a slightly early peak in the storm surge while the NOGAPS forcing produces an even earlier arrival of the peak surge. The 60 km RMW forecast case and the three hindcast cases closely predict the estimated time of maximum surge while the 90 km RMW forecast case peaks too soon. Both of the forecast cases produce more reasonable water level values before and after the peak surge than in any of the three hindcast experiments.
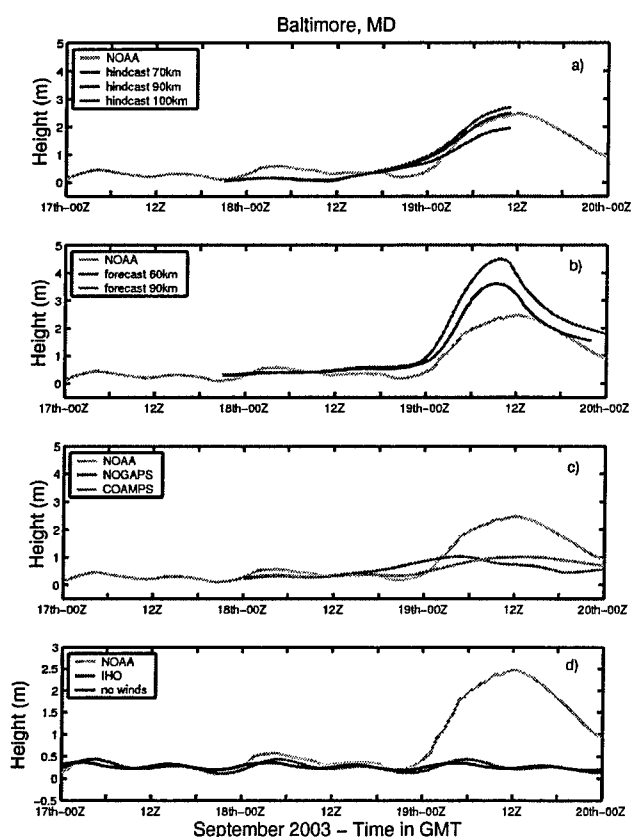
surge larger than the last recorded observation. The COAMPS and the two forecast cases have the best estimate of forecast peak arrival with the COAMPS prediction approximately half an hour off. At the Baltimore station, similar trends appear in the COAMPS/NOGAPS cases. The hurricane forecast cases peak slightly too soon and overestimate the height of the surge. However, the hindcast experiment (90-100 km RMW) for Baltimore shows very good agreement at peak surge with the observed water level.

The only wind observation available was at the Solomons Island station. Figure 14, the observed and modeled winds at the Solomons Island station, show that the maximum wind occurred sometime after 0200Z on the 19th. If the timing of the peak winds corresponds to the peak surge, then this arrival time corresponds well with our previous estimate of the timing of peak surge.

Figure 13. Observed water level above MLLW at the Baltimore, MD station versus a) Holland Model hindcast using 70 km RMW , 90 km RMW and 100 km RWM, b) Holland model forecasts using 60 km RWM and 90 km RMW, c) NOGAPS and COAMPS forecast driven tidal height and d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z September 20th.

At the Solomons Island station, the COAMPS and NOGAPS cases each underestimate the peak level of surge while the hindcast and forecast cases predict a

Figure 14. Observed wind a) speed and b) direction versus modeled wind speed and direction from the 7 models used in this study at the Solomons Island station.

Although the magnitude of the winds is underestimated by both the NOGAPS and COAMPS models, the direction of the COAMPS winds are in better agreement with observations. The hurricane hindcast winds, particularly using the 70 km RMW, appear to be the best estimate of wind speed. The hurricane forecast winds

appear far too strong. Note that in this case the forecast hurricane has not passed directly over the Solomons Island station.

5. Discussion

Based on the NOAA observations, peak water levels at the 8 stations considered in this study occurred at the times and with the maximum water levels shown in Table 2.

Station	Time	Height (m)
Beaufort	1840Z, 18th	1.754
Cape Hatteras	>1400Z, 18th	>2.341
Duck	>1600Z (1800Z),18th	>2.383
Virginia Beach	1820Z, 18th	2.297
Chesapeake Bay	1820Z, 18TH	2.297
Windmill Point	2324Z, 18th	>1.060
Solomons Island	0452Z, 19th	>1.363
Baltimore	1200Z, 19th	2.483

Table 2. Observed peak water level above MLLW for each station.

The stations on the eastern side of the storm located near the point of landfall exhibit some of the highest water levels. As the storm moved north-northwest and weakened, the next stations affected experienced slightly lower levels of maximum surge. In Chesapeake Bay, the observations indicate that the water level increased during the storm from south to north along the Bay, with maximum water levels observed at the northernmost station, Baltimore. Although the storm had weakened from its intensity at landfall, the maximum surge at Baltimore was similar to that at the Cape Hatteras and Duck stations. With the observed storm path taking it to the west of the Bay, the winds were predominantly from the east then south pushing water continuously northward into the Bay causing the high water at Baltimore.

The PCTides model was used to evaluate the effects of hurricane Isabel on water levels along the east coast of the United States. To determine the ability of the PCTides system to forecast water level variations due to tidal forcing alone, the system was run with no wind forcing and compared to the tidal forecasts calculated from IHO constituent data and the observed water levels at each station used in this study. These results are plotted in Figure 4-6, 8-9 and 11-13 in panel (d). The PCTides solution agrees well with the IHO solution and the observations in most cases. At the Duck station, the PCTides solution is in better agreement with the observations than the IHO forecast. Again, it is

important to note that in none of the experiments associated with this study was any data assimilated into the PCTides model. At the North Carolina and southern Virginia stations where the maximum tide coincided with the maximum storm surge, the tidal amplitudes were approximately 25-30% of the total increase in water level above the mean.

The PCTides model was used to predict storm surge in a forecast mode. The forecast models applied to this test were complete atmospheric forecast systems represented by the NOGAPS and COAMPS models and a simpler hurricane forecast model. PCTides was then run, after the storm passed with the observed track and storm intensity using the hurricane model. Table 3 shows the Absolute Mean Error (AME) and Root Mean Square Error (RMS) of the peak surge associated with each model run. Values in parentheses were calculated using only the Beaufort, NC; Chesapeake, VA and Baltimore, MD, those three stations with uninterrupted observations throughout the storm.

Model	Height (meters) AME RMS	Time (minutes) AME RMS
COAMPS	.62(.79) .76(.95)	75(58) 90(64)
NOGAPS	.72(.88) .83(1.0)	148(193) 305(254)
Forecast 60	.52(.49) .63(.68)	90(128) 121(120)
Forecast 90	.68(.84) .94(1.1)	168(100) 170(100)
Hindcast 70	,45(.70) .55(.61)	134(68) 182(69)
Hindcast 90	.25(.42) .39(.60)	112(68) 51(69)
Hindcast 100	.22(.43) .38(.55)	110(65) 50(68)

Table 3. Absolute Mean Error (AME) and Root Mean Squared (RMS) Error associated with the prediction of the time and amplitude of peak storm surge for each PCTides simulation. The values in the parentheses were calculated only using the Beaufort, NC, Chesapeake, VA and Baltimore, MD stations.

Table 4 (see next page) shows the peak water level and time of peak surge for each of the stations and simulations. Those values "bolded" represent the most accurate of the hindcast/forecast results for stations.

Model	Beaufort		Cape Hatteras		Duck		Virginia Beach		Chesapeake		Windmill		Solomons Island		Balt
	Time 9/18/04	Height (m)	Time 9/18/04	Height (m)	Time 9/18/04	Height (m)	Time 9/18/04	Height (m)	Time 9/18/04	Height (m)	Time 9/18-19/04	Height (m)	Time 9/19/04	Height (m)	Time 9/19/04
COAMPS	**1800Z**	**1.564**	1700Z	1.677	1812Z	2.077	**1824Z**	**1.188**	1900Z	1.594	2200Z	0.946	0424Z	0.943	1336Z
NOGAPS	1800Z	1.466	1712Z	1.419	0424Z	1.523	1636Z	1.452	1712Z	1.346	2100Z,	0.930	0200Z	1.025	0448Z
Forecast 60	1700Z	1.382	1036Z	1.418	1500Z	2.224	1724Z	2.787	**1836Z**	**2.296**	**2324Z**	**1.459**	**0348Z**	**2.088**	0912Z
Forecast 90	1700Z	1.385	0824Z	1.534	1336Z	2.078	1612Z	2.783	1712Z,	2.425	2024Z	1.401	0348Z	2.320	0948Z
Hindcast 70	2000Z,	1.363	1648Z	2.301	1800Z	2.005	1836Z	1.761	1912Z	1.120	0100Z	0.656	1236Z	1.213	1048Z
Hindcast 90	2000Z	1.504	**1636Z**	**2.376**	1800Z	2.254	1900Z	2.081	1912Z	1.283	0000Z	0.800	1136Z	1.484	**1048Z**
Hindcast 100	**1948Z**	**1.591**	**1636Z**	**2.352**	**1748Z**	**2.387**	**1900Z**	**2.245**	1924Z	1.375	0000Z	0.874	1136Z	1.593	1048Z
Observation	*1840Z*	*1.754*	*>1430Z*	*2.341*	*>1600Z*	*2.383*	*1820Z*	*2.297*	*1820Z*	*2.297*	*2344Z*	*>1.060*	*0456Z*	*>1.363*	*1200Z*

Table 4. Maximum observed, forecast and hindcast water levels for the 8 stations.

The PCTides model run in the hindcast mode using an estimated RMW of 100 km provided the best overall forecast of storm surge with the smallest RMS error for both height and timing of the peak surge. This case produced the best forecast at all stations except those in the lower Chesapeake Bay. However, we were required to estimate the time and amplitude of peak surge at both the Windmill and Solomons Island stations and may have error associated with our estimates. It should be noted that the hindcast simulation along the coast at Virginia Beach agreed more closely to the Chesapeake Bay observations, than at the modeled Chesapeake Bay station (in the mouth of the Bay) implying that there might be additional effects coming into play at the mouth of the Bay that are not included in these simulations (such as river runoff). Therefore, with the correct path (the hindcast track) and a reasonable estimate of the magnitude of the storm, PCTides does show credibility in forecasting storm surge generated by the storm.

An important issue for this study is how well we can "forecast" the storm surge. Of the two simulations driven by atmospheric forecast models, the COAMPS simulation had the best agreement with observation. COAMPS often produced a reasonable estimate of the time of peak surge, on average off by < 75 minutes, but always produced a maximum water level below the observed. This bias is most likely due to the under estimate of the wind speed by the model (Figures 7a, 10a and 14a). The forecast driven by NOGAPS often produced estimates of the time of peak surge that were similar to those produced by the COAMPS run however the predictions at Baltimore and Duck were substantially different from the observations. In addition, NOGAPS forecast peak wind speeds were generally weaker than the COAMPS forecast winds. As a result, surge forecasts driven by NOGAPS had a slightly lower bias in the predicted maximum water level than the COAMPS forecasts. The COAMPS model is run at higher resolution (27 km) than the NOGAPS (81 km) model, which may account for the more accurate forecasts.

The simulations driven by the Holland model's forecasts were based on observations and a forecast track estimated by the NHC in their 2100Z advisory/forecast on September 17th. The storm track based on that forecast had a bias that took it to the east of Isabel's actual track. In addition, the forecast model assumed a constant average central pressure and a constant translational velocity for the storm throughout the forecast. As was seen in Isabel, the storms forward motion increased substantially after landfall. Even with the uncertainty in the path and storm definition, these forecast storms produced reasonable results. The 60 RMW and 90 RMW case were off, on average, on the timing of peak surge by 90 minutes and 168

minutes respectively. These forecasts generate peaks in storm surge that occur too early at the southern stations, but are close to the observed times for the stations midway along the path (Chesapeake, Windmill, and Solomons Island) and predict late peaks in the storm surge at the end of the track (Baltimore). This trend is associated with the constant forward motion of the storm versus the observed initial slow motion and then acceleration of the storm after landfall. In both cases the forecasts under estimate the storm surge in the early part of the track and over estimate the water level in the latter part of the track. The forecast storm with the smaller radius of maximum wind (60 km) provided the better overall forecast of the two cases even though the observed RMW corresponded to the 90 km case. In the 60km RMW storm, strong winds cover a smaller area than in the 90 km RMW storm. As the storm track was shifted closer to the stations we used in this study, this probably accounted for the slightly better estimates of maximum surge in the 60 km RMW case.

It should be noted that the forecast track used to generate a storm with the Holland model, was based on advisory/forecast information available only 20 hours prior to landfall, and still generated a path with an eastward bias of approximately 150 km. The PCTide simulations are neither computer intensive nor difficult to set up and execute, therefore several estimations of forecast tracks should be used to provide a range of forecast scenarios prior to the landfall of a storm.

6. Summary and Conclusion

Hurricane Isabel made landfall along the mid North Carolina coast and continued on a north-northwesterly path for the next several days affecting Virginia, Maryland, Delaware, West Virginia, Pennsylvania, New Jersey, New York and Rhode Island.

Along with wind and rain, storm surge had a major impact on coastal residents. The track of hurricane Isabel produced strong easterly and southerly winds along the North Carolina, and Virginia coasts as well as in Chesapeake Bay. Maximum water levels, generated as a combination of tides and storm surge, were observed to be greater than 7.5 feet in places like Baltimore. The ability to accurately predict the timing and intensity of the storm surge would provide valuable warning to both residents and businesses along the storm's path.

Numerical models provide a useful tool in predicting the effects of the surface wind and pressure fields associated with a tropical cyclone on the storm surge. A number of various scenarios can be generated and simulated by the numerical models before these storms make landfall providing the

public with a range of estimates of the impact of the storm.

This study showed that the PCTides model, driven by various atmospheric model forecasts, has the ability to provide useful estimates of the combined tide and storm surge generated by a passing hurricane. The model's ability to predict the storm surge is directly dependent upon the accuracy of the atmospheric forecast of the track and intensity of the storm.

Acknowledgements

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14. ABSTRACT
On the 6th of September 2003, a westward moving tropical wave in the far eastern Atlantic began to organize and evolve into tropical storm Isabel. By September 7, Isabel had become a full-fledged hurricane and began to move west-northwest. Isabel continued her northwest track through the 8th and 9th, intensifying into a major hurricane. By September 11th, Isabel had become a Category 5 hurricane on the Saffir-Simpson Scale, and maintained this high level of intensity through September 15th. During this time Isabel took a more westward track, until it began to turn northwestward on the 15th. On the 16th, Isabel began to weaken and headed in a north-northwestward direction toward the North Carolina coast. On September 18th, at approximately 17Z, Isabel made landfall near Drum Point, North Carolina as a Category 2 hurricane with sustained winds near 100 mph and a minimum central pressure of 957 mb. Hurricane forecast winds extended 115 miles from the center of its large eye with tropical storm force winds extending 345 miles out from the center. By 1500Z (11 am EDT) on September 19th, Isabel was downgraded to a tropical depression located northeast of Cleveland, Ohio and was moving rapidly to the north. Numerical ocean models can be used to both forecast and hindcast storm surge events. These models use the wind and pressure forcing associated with a hurricane or tropical storm to determine the magnitude of the associated storm surge.

15. SUBJECT TERMS
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